A VIMOS-IFU survey of $z \sim 0.2$ massive lensing galaxy clusters: constraining cosmography

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Summary. We present an integral field spectroscopy survey of rich clusters of galaxies aimed at studying their lensing properties. Thanks to knowledge of the spectroscopic caracteristics of more than three families of multiple images in a single lens, one is able in principle to derive constraints on the geometric cosmological parameters. We show that this ambitious program is feasible and present some new results, in particular the redshift measurement of the giant arc in A2667 and the resdshift confirmation of the counter-image of the radial arc in MS2137–23. Prospects for the future of such program are presented.

1 Cosmological applications of gravitational lensing

Gravitational lensing has been deeply renewed since 15 years now, and many extensive reviews are available in the litterature [1]. So we simply remind here the basic lensing equation, which corresponds to a mapping of the image plane on the source plane

$$\boldsymbol{\beta} = \boldsymbol{\theta} - \boldsymbol{\nabla}\psi(\boldsymbol{\theta}) \qquad\qquad \psi(\boldsymbol{\theta}) = \frac{2}{c^2}\frac{D_{LS}}{D_{OS}D_{OL}}\varphi(\boldsymbol{\theta})$$

where $\varphi(\boldsymbol{\theta})$ is the newtonian gravitational potential of the deflecting lens. The distances are angular-distances between the lens, the source and the observer. The Einstein radius, defined as

$$R_E = \sqrt{\frac{4GM}{c^2}\ \frac{D_{OL}D_{LS}}{D_{OS}}} = 2.6'' \left(\frac{\sigma^2}{c^2}\right)\frac{D_{LS}}{D_{OS}}$$

represents the radius of the circular image in the ideal case of a source perfectly aligned behind a point source of mass M or behind a singular isothermal sphere with velocity dispersion σ. For any lensing mass, it represents the typical angular scale of the lensed images. Numerically, it is about $1 - 3''$ for a galaxy lens and $10 - 30''$ for a cluster of galaxies. In practice, gravitational lensing has many astrophysical applications, related to either the determination of the lensing potential and the mass distribution in galaxies and in

clusters of galaxies, or the study of the distant galaxies thanks to the magnification of their images [2]. But it also depends on the geometrical cosmological parameters and represents an alternative possibility to constrain these parameters, independantly from other methods like supernovae or CMB fluctuations. This method was explored recently in details [3]. It requires several sets of multiple images from different sources at different redshifts through the same lens. For each source the lens equation can be written as

$$\boldsymbol{\theta}_S = \boldsymbol{\theta}_I - \frac{2\sigma_0^2}{c^2}\boldsymbol{f}(\boldsymbol{\theta}_I, \theta_C, \alpha, \ldots) \times E(\Omega_M, \Omega_\Lambda, z_L, z_S)$$

where the f function includes all the caracteristics of the lensing potential and $E = D_{LS}/D_{OS}$ includes the cosmological dependence [$(\Omega_M, \Omega_\Lambda)$ or (Ω_M, w) for an euclidian universe] as well as the lens and source redshifts. Provided z_L and z_S are well known for two sets of multiple images, one can in principle solve the lens equation for both sets and constrain the E-term, with a well-defined degeneracy between the two geometrical cosmological parameters used [3]. However the cosmological dependence in the E-term is weak and better constraints require more than two sets of multiple images, spread in redshift as well as a very accurate mass determination in the lens (Fig. 1).

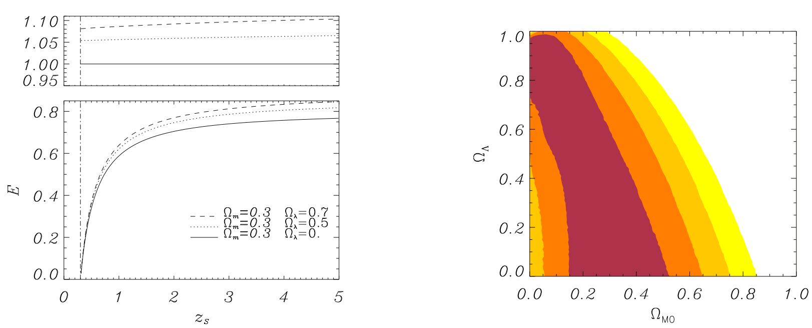

Fig. 1. Left: Evolution of the E-term with redshift for different cosmological models, for a lens at $z = 0.3$. Right: Confidence levels obtained from the modeling of the cluster-lens Abell 2218 [5]

This method was first attemped in the cluster Abell 2218 ($z_L = 0.17$,), a strong gravitational lens close to the ideal case: it displays at least 4 sets of multiple images with redshifts ranging from $z_{S1} = 0.702$ to $z_{S4} = 5.576$. An accurate mass model was developped [4], including 2 major mass components located on the two brightest galaxies, as well as the contribution of about 17 galaxy masses scaled by their luminosity. This model prescription was constrained more accurately by including the 4 families of multiple images, and the likelihood distribution in the $(\Omega_M, \Omega_\Lambda)$ plane finally displayed the expected degeneracy (Fig. 1), reinforcing the validity of the mass model [5].

2 Observations of massive lensing clusters with VIMOS/IFU

In order to tighten the likelihood distribution in the $(\Omega_M, \Omega_\Lambda)$ plane we need to add more cluster-lenses with similar numbers of multiple images but different lens redshifts or mass distributions. This is the main motivation of a survey of massive cluster lenses started two years ago at ESO and using the IFU mode of VIMOS on the VLT. This instrument configuration has many advantages, thanks to its wide field of view of $1' \times 1'$ in order to get as many redshifts as possible, both on cluster galaxies and on lensed arcs with curved shapes. The high density of objects in the central cores of clusters is therefore mapped in a single shot, allowing both to study the dynamics of the cluster galaxies and the redshift determination of the brightest multiple arcs.

Table 1. Summary of the VIMOS/IFU observations of the survey

Cluster	redshift	# pointings	Run	T_{exp} (ksec)
Abell 1689	0.184	4	May-June 2003	59.4
Abell 2390	0.233	3	June 2003	32.4
AC 114	0.312	2	June 2004	21.6
Abell 2667	0.233	1	June 2003	10.8
MS2137–23	0.310	1	June 2003	10.8
Abell 68	0.255	1	August 2004	5.4

Up to now, 6 clusters have been observed in low resolution mode ($R \sim 200$), with a usefull spectral range from 4000 to 6800 Å(Table 1). Most clusters have a redshift in the range 0.2–0.3 which is optimal for our programue. Data reduction was rather tricky, and is presented in details in [6].

2.1 Abell 2667

Abell 2667 was observed with IFU/VIMOS in a single pointing, splitted in 4 exposures of 45 mn each [6] . It is a strong X-ray emitter and multi-color HST imaging revealed a very prominent and bright luminous arc corresponding to 3 merging images. Its spectrum was extracted and splitted in 3 for each sub-image. The redshift confirmation is obvious in this case (Fig. 2). A few very faint multiple images candidates were also identifed. However, by exploring the final datacube, we were not able to determine more new arc redshifts, preventing the use of A2667 for cosmological purposes. But with the present data, we were able to determine the redshift of more than 20 cluster members, so a first value of the velocity dispersion could be used for the lens modeling. A detailed lens model was therefore built and the mass distribution compared with the mass deduced from X-ray data and the virial mass [6] (see also Covone's talk, these proceedings).

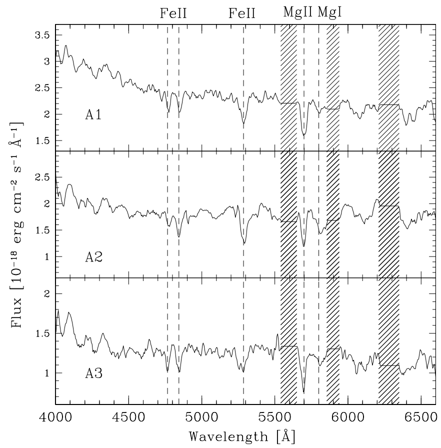

Fig. 2. Spectra of the three sub-images of the giant arc in A2667, with line identifications at redshift $z = 1.03$.

2.2 MS2137–23

MS2137–23 is a well known gravitational lens with two independant systems of lensed images: one tangential arc with its two counter-images and one radial arc with its counter-image candidate. The two main arcs have been observed spectroscopically with a redshift measurement at a redshift $z \simeq 1.5$ for both systems [7]. Unfortunately this is not favorable for cosmography although this lens is studied in details in order to constrain the properties of the mass distribution in the very center of clusters [8]. However, from the datacube built from our observations (2 exposures of 45mn each), we were able to extract the spectrum of the counter-image of the radial arc (A5), confirming its redshift at $z = 1.503$ (Fig. 3). This is the first redshift confirmation that A5 is the counter-image of the radial arc.

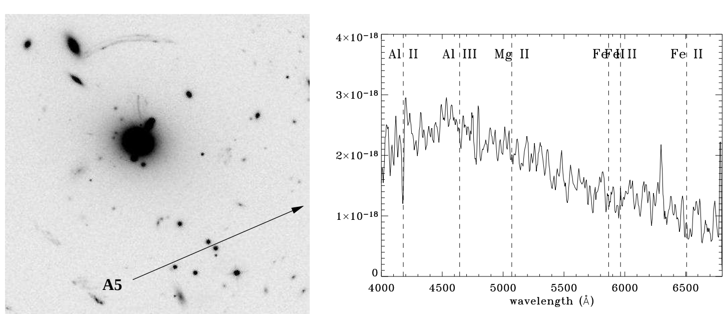

Fig. 3. Integrated spectrum of the counter-image of the radial arc in MS2137–23, and the line identification with redshift $z = 1.503$.

2.3 Abell 1689: the ultimate lens !

Fortunately, there exits presently at least one cluster-lens which deserves great attention because of its unprecedented number of arcs and arclets. From deep HST/ACS observations of Abell 1689, more than 30 systems of multiple images are identified in the center [9]. The lens has a complex mass distribution and its lens modeling is not easy. In addition only a few multiple images presently have measured redshifts, because of their faintness. We have started an VIMOS/IFU survey of this lens in 2003, when the instrument was not completely stabilized. This prevented an accurate data reduction, although we still hope to extract some exciting results from the datacubes. However, several spectroscopic redshifts are already available, in particular from previous long slit observations and we should be able to provide a good lens model as well as some new constraints on cosmography. Note that a preliminary attempt [9] did not give interesting constraints, partly because they used photometric redshifts only, for most of the arcs. The key point will be clearly to include additive contraints on the lens model either from weak lensing measurements at large distance or from X-ray data.

3 Conclusions and prospects

We have started an ambitious observing programme, well suited to 3D spectroscopy and aimed at studying in details a sample of strong gravitational lenses. The main difficulty is the faintness of the arcs which requires to push the present spectrographs to their limits. The results are therefore very sensitive to the data quality at the output of the telescope and to the data reduction which must be done with great care. These fundamental steps are in progress and we have demonstrated that faint objects 3D spectroscopy is feasible in rich environments like clusters of galaxies. Several scientific outputs from these data are presented, others are in Covone's talk (these proceedings) concerning the properties of the cluster galaxies.

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